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Quantum Simulation and Quantum Sensing with Ultracold Strontium

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14. ABSTRACT
We have built an ultra-high vacuum experimental apparatus for trapping and cooling of strontium, demonstrated its operation, and used it to trap and cool all four stable isotopes of this alkaline earth metal. As part of the design and construction of this apparatus, we have developed a new type of atomic beam nozzle and a new type of permanent-magnet Zeeman slower. We have discovered and described a new cooling technique for degenerate bosonic quantum gases in optical lattices. We have developed the first theoretical treatment of a lattice-based quantum Kapitza pendulum, a novel Floquet system which we are investigating using modulated optical lattices. We have proposed and are developing new techniques of quantum gas microscopy and quantum sensing applicable to alkaline earth quantum gases. We have helped found a new collaborative institute for quantum emulation.

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1 Design, construction, and operation of experimental apparatus

To enable the goals of our AFOSR YIP project we have designed and built a flexible cold strontium apparatus. Construction is complete, and we have trapped all four stable isotopes of strontium. A diagram and photo of the experimental setup appears in Fig. 2. The strontium trap is loaded from an effusive oven which contains a multi-isotope source. As the atom trap requires ultra-high vacuum, an adequate pressure ratio between the oven and trapping regions is maintained by two 40 L/s ion pumps in a double differential pumping configuration. In order to achieve both a high atomic flux and tight beam collimation, we designed and built a new kind of atomic beam nozzle consisting of a close-packed array of stainless steel microcapillaries (see Fig. 1). We have published a paper describing the design and experimental implementation of this nozzle [1]. The bulk of the atomic beam is decelerated by a Zeeman slower with a laser detuned 750 MHz from the $(5s^2)^1S_0 - (5s5p)^1P_1$ transition at 461 nm. As part of the construction of the strontium experiment, we designed and built a new kind of permanent-magnet Zeeman slower suitable for alkaline earth atoms, shown in Fig. 3. We reported the permanent-magnet design (which may be especially relevant to low-cost or spaceborne experiments) and an analysis of its performance in another publication [2]. Transverse cooling light provides further beam collimation in order to maximize the atomic flux into our main chamber.

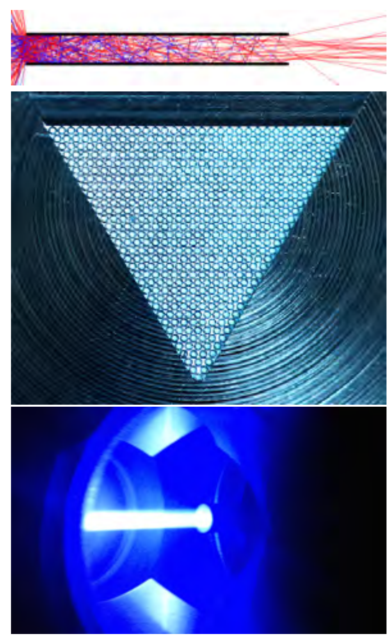
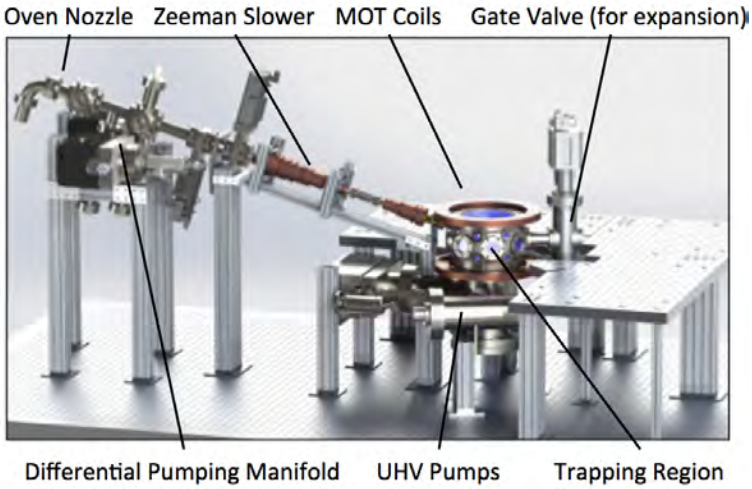


Figure 1: Nozzle and atomic beam. **Top:** Simulation of particle trajectories through a collimating nozzle tube. **Middle:** Photograph of nozzle array. **Bottom:** Atomic beam of strontium from nozzle scattering light from the slower laser.

The slower loads a Magneto-optical Trap (MOT) operating at 461 nm. The MOT has a capture velocity of order 25 m/s and a final temperature of approximately 4 mK, which is limited by the relatively broad 32 MHz transition linewidth. Ground state atoms are nonmagnetic, and thus must be trapped optically. To simplify optical evaporation, we employ the Katori cooling scheme [3], which utilizes additional cooling on the $(5s^2)^1S_0 - (5s5p)^3P_1$ intercombination line (see Fig. 7 for a spectroscopic diagram of strontium). This triplet state (along with the $(5s5p)^3P_2$ state) is populated due to a leak in the cycling transition of the 461 nm MOT. The quadrupolar magnetic field of the MOT acts as a trap for the now magnetic triplet-state atoms. We use 403 nm light operating on the $(5s5p)^3P_2 - (5s6d)^3D_2$ transition to pump atoms from the otherwise inaccessible and long-lived $(5s5p)^3P_2$ state to the $(5s5p)^3P_1$ state (see Fig. 4). A MOT operating on the intercombination line at 689 nm performs further cooling to approximately 2.5 μK, now only limited by the narrow 7.4 kHz natural linewidth. In the



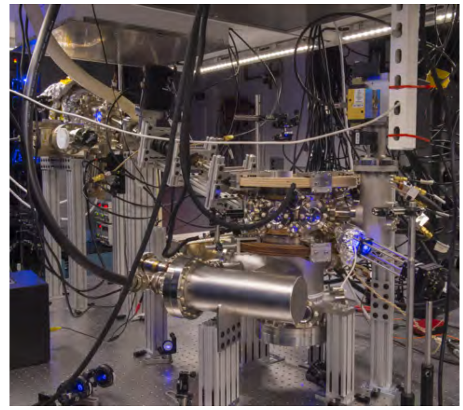


Figure 2: UCSB strontium apparatus. **Left:** Diagram of the strontium machine design. **Right:** The assembled machine in the PI's lab, with optical breadboards removed.

next stage of cooling, the atoms are loaded into a crossed optical dipole trap (ODT), where evaporative cooling to degeneracy can proceed via trap weakening. Due to strontium's relatively small isotope shifts, we are able to trap any of the four stable isotopes of strontium in our apparatus, including three bosonic species (^{84}Sr, ^{86}Sr, and ^{88}Sr) and one fermion with a high nuclear spin of 9/2 (^{87}Sr). Fig. 4 shows fluorescence from all four species, loaded together into a magnetic trap within a second.

Much of the complexity of an all-optical BEC experiment (particularly for non-alkali atoms) is in the cooling laser sources. For purposes of trapping and cooling, we have set up a frequency-doubled diode laser source at 461 nm, locked to a strontium vapor cell, and diode lasers at the intercombination line of 689 nm and appropriate repumping wavelengths (a doubled source at 497 nm and a direct-diode at 403 nm, conveniently close to the Blu-ray wavelength).

The experimental chamber was fabricated from 316L stainless steel and equipped with 11 pairs of windows antireflection coated at the appropriate wavelengths, including one pair for the mid-IR transitions needed for achieving certain advanced schemes of quantum gas microscopy or inducing long-range interactions [4]. A "turret" design provides high conductance to the 75 L/s main chamber ion pump and titanium sublimation pump while allowing excellent 360° optical access to the atoms. The port configuration is designed to allow for reconfigurable lattice geometries. Flexible optical access is also critical for our most important readout techniques, which include absorption imaging, fluorescence, and recently developed advanced probes of correlation such as optical Bragg diffraction [5]. A large-bore all-metal gate valve is attached to the one of the windows, enabling expansion of experimental capabilities without breaking the main chamber vacuum. We have designed the apparatus to be flexible and expandable, including a transport axis and the valve for a future quantum gas microscope or near-surface sensing chamber and long-time-of-flight "drop ports" for high-contrast Stern-Gerlach separation of nuclear spins or atom interferometry. This flexibility will ex-

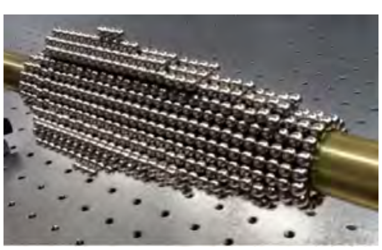


Figure 3: New type of Zeeman slower made of permanent spherical magnets.

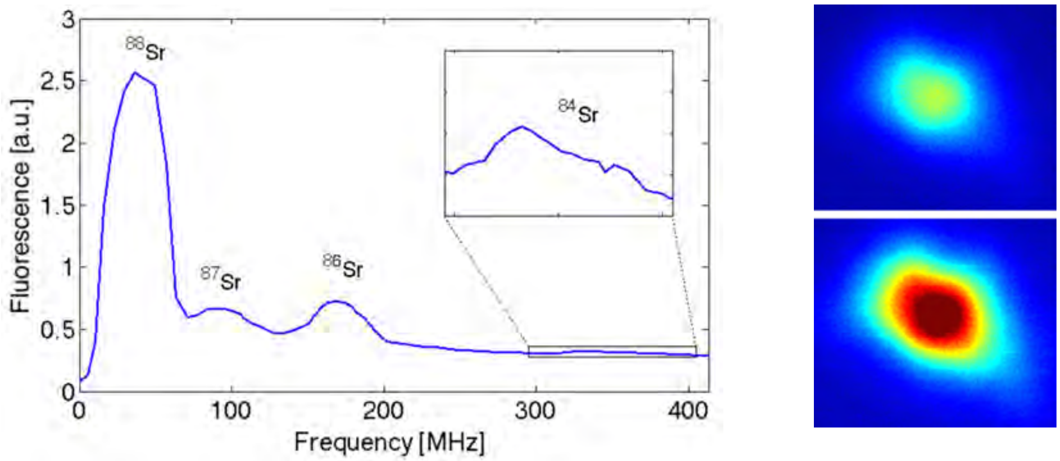


Figure 4: Trapping all four stable isotopes of strontium. **Left:** As the frequency of the main trapping laser at 461nm is scanned, we observe fluorescence from MOTs of all four stable isotopes of strontium. Differing peak heights are due to natural isotopic abundance. While each MOT is being loaded, atoms are continuously "leaked" into the dark magnetically trappable metastable state, so that after a scan such as that presented here, a four-isotope mixture is present in the trap. **Right:** False-color fluorescence image of the trapped strontium before (top) and after (bottom) application of a 403nm repumper. The difference is due to trapped metastable $^3P_2$ atoms.

tend the useful scientific lifetime of the apparatus that we have developed with support from our AFOSR YIP award, enabling a variety of future experiments on quantum simulation and quantum sensing.

2 Novel cooling techniques

The development of novel cooling techniques for ultracold gases was a major goal of our AFOSR YIP project. Having recently developed the theory of and experimentally demonstrated spin gradient demagnetization cooling [7,8], we proposed to explore new cooling techniques applicable to ultracold bosons and fermions. This led, via an investigation of dilution cooling, to a new study of adiabatic entropy-pumping techniques which operate at the single-lattice-site level. In collaboration with the MIT and Strathclyde groups, we recently suggested and analyzed a new scheme to adiabatically cool bosonic atoms to picokelvin temperatures [6]. The starting point is a gapped phase called the spin Mott phase where each site is occupied by one spin-up and one spin-down atom. An adiabatic ramp leads to an xy-ferromagnetic phase. We have shown that magnetic correlations are robust for experimentally realizable ramp speeds and decoherence times. Due to different ground-state symmetries, we also find a metastable state with xy-ferromagnetic order if the ramp crosses to regimes where the ground state is a z-ferromagnet. The bosonic spin Mott phase as the initial gapped state for adiabatic cooling has many features in common with a fermionic band insulator, but the use of bosons should enable experiments with substantially lower initial entropies. Cooling techniques of the type we report are a critical ingredient for future efforts at quantum emulation and also, in the longer term, quantum sensing.

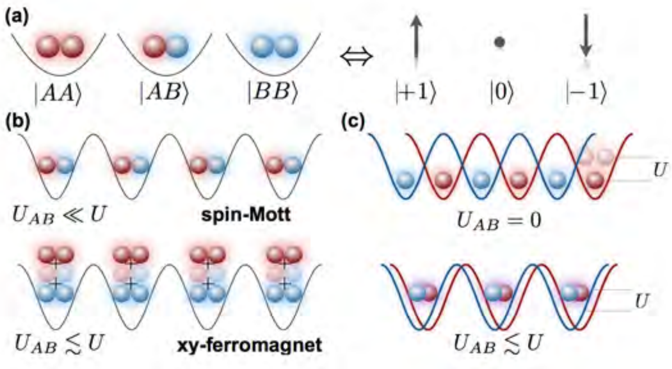


Figure 5: Adiabatic cooling with the spin Mott state. **a:** Two-component bosons on a single lattice site with occupation number two and strong interactions can be represented as three different spin-1 states. **b:** When the inter-component interaction U_{AB} is negligible compared to the intra-component interaction U, the ground state of the system corresponds to a spin Mott state, for $U_{AB} \lesssim U$ to a planar xy-ferromagnetic state, shown here as a mean-field depiction. **c:** Spin-dependent lattices can be used to adiabatically tune the system from a spin Mott state to an xy-ferromagnetic regime. Figure adapted from Ref. [6].

3 Lattice Modulation

The development of techniques of lattice modulation for controlling transport and improving quantum force sensing was another goal of our AFOSR YIP project. To this end, we have developed the first theoretical treatment of a lattice-based quantum Kapitza pendulum. We have identified one of the simplest Floquet phases accessible with cold atoms or indeed with any experimental system: a Floquet-Kapitza crystal. A classical single-particle analogue of this phase occurs in a rigid pendulum with an oscillating support (known as a Kapitza pendulum [9]). To prepare for experiments using deeply non-classical ultracold atoms, we have recently extended the analysis of this system to the quantum realm. Our results on the nonequilibrium quantum phase diagram of the Kapitza lattice, shown in Fig. 6, indicate that the features expected from classical intuition persist in the quantum regime. In a strongly modulated lattice, changes in the amplitude and frequency of the drive allow exploration of a rich stability diagram comprising three distinct stable phases as well as an unstable phase that absorbs unbounded energy from the drive. Our calculations predict that a Floquet Kapitza crystal with half the original lattice constant will emerge in certain regions of the parameter space (the

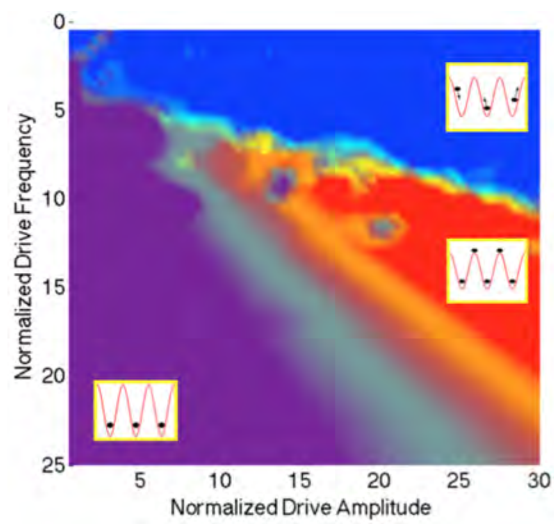


Figure 6: Calculated nonequilibrium phase diagram of Kapitza lattice, as a function of drive amplitude and frequency. The purple region supports a non-inverted phase, the blue region is unstable, and the red region supports the Kapitza crystal.

red are of Fig. 6), breaking translation symmetry in a way fundamentally different from that of any undriven system.

We have not yet reported these new theoretical results because we believe we are close to realizing the first experiments on this novel system. Measuring the effect of large-amplitude lattice modulations as a function of frequency and amplitude will allow exploration of the effects of quantum correlations [10], interatomic interactions, dimensionality, and dissipation on the dynamic stabilization of this novel driven system. This will open up an entirely new angle of attack on tunable Floquet systems, currently a topic of intense interest in the condensed matter community. One practical goal of this experiment is to realize switchable localization of atoms at lattice potential maxima, in analogy to the inverted pendulum, which would provide a powerful tool for engineering nearest-neighbor interactions in a quantum simulator. The simplest observable we will use to characterize Floquet-Kapitza phases is energy absorption, measurable as a function of drive parameters via time-of-flight calorimetry. Projection onto a static lattice and subsequent bandmapping will be used to demonstrate "inverted" localization at potential maxima. Optical Bragg diffraction, a technique pioneered by the PI and colleagues [5], will be employed to probe periodic ordering in an emergent Floquet-Kapitza crystal.

4 Quantum gas microscopy

The flexible design of our YIP-supported cold strontium apparatus has enabled us to recently begin exploration of a new research direction: alkaline earth quantum gas microscopy (QGM). Although our research in this direction is in the early stages, we discuss it here because it springs directly from the goals and design of the AFOSR YIP project. QGM allows imaging and control of individual atoms in a deeply quantum-degenerate sample. Although until very recently only two quantum gas microscopes existed, these devices have enabled a startling number of breakthroughs in the last few years [11–18, e.g.]. QGM with strontium would open up a number of otherwise-inaccessible research prospects in the investigation of exotic quantum phases, simulation of complex materials, and quantum sensing. A recently awarded DURIP, funded at 55%, has enabled us to purchase some of the equipment for developing a strontium QGM. The QGM we are designing will build on existing methods while also taking advantage of the unique properties of strontium to enable new techniques of control and detection. Below we briefly outline the results of our preliminary research into strontium-specific paths to single-site resolution, omitting discussion of techniques such as high-NA optics and efficient imaging which are common to all quantum gas microscopes.

Magic Lattice Microscopy: The intercombination transition in strontium allows very low Doppler temperatures, meaning that atoms illuminated with 689nm cooling light can remain in a lattice of modest depth during imaging. To avoid inhomogeneous AC Stark shifts of the narrow line, the lattice laser must operate at the magic wavelength of 915nm. This simplest approach to alkaline earth quantum gas microscopy is the initial focus of our research.

Narrow-Line Tomography: Strontium's narrow intercombination transitions enable sharp tomographic imaging and addressing of "slices" of ultracold gases [19]. By allowing optical selection of individual lattice planes, this could enable the first truly three-dimensional QGM.

Bio-Inspired Imaging: Another method of strontium-enabled next-generation quantum gas microscopy is the adaptation of sub-diffraction imaging techniques such as Stochastic Optical Reconstruction Microscopy (STORM) from the field of biology. This technique would essentially

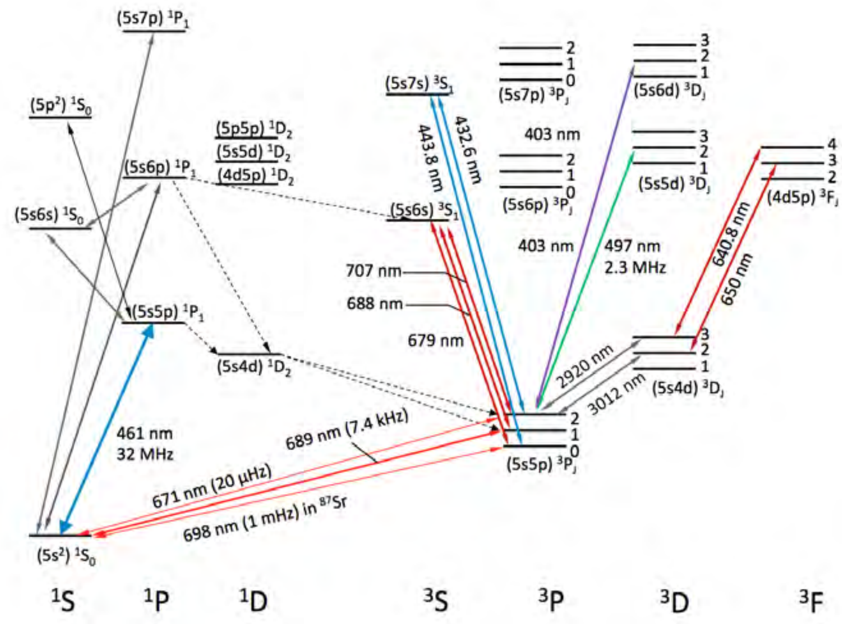


Figure 7: Energy level diagram for strontium. Relevant wavelengths and linewidths are noted.

treat strontium as a photoswitchable dye, using the metastable $(5s5p)^3P_2$ state to turn on and off fluorescence with high fidelity. Super-resolution is enabled by switching on only a subset of emitters at any given time, allowing the accurate reconstruction of the center position of each emitter. A small grant from UCSB is enabling us to explore initial implementation of this technique, which has not to our knowledge been proposed elsewhere.

F-state Microscopy: Tunable mid-IR lasers can be used to populate the $(5s4d)^3D_J$ states in strontium. Transitions from these states to the $(4d5p)^3F_J$ manifold should allow sub-Doppler cooling during fluorescence imaging, although the detailed implementation of this technique, particularly in a magic lattice, may be affected by incompletely known spectroscopic properties of strontium's G states. This is essentially a three-photon microscopy technique.

Excited-State Light Shift Microscopy: In this approach, an analogue of which was very recently demonstrated in Ytterbium, a lattice at 1130nm confines atoms in the ground state. Application of intense light at 461nm drives Rabi oscillations to the $(5s5p)^1P_1$ state. Due to an 1120nm transition to the $(5s6s)^1S_0$ state this excited $^1P_1$ state sees a very large AC Stark shift from the pinning lattice. For sufficiently high Rabi frequencies, the atoms then feel an effective averaged potential which is deep enough to confine them during fluorescence imaging. Intriguingly, the imaging time in this approach is four orders of magnitude shorter than in a Rb-based microscope. However, differences in the detailed atomic properties of Yb and Sr may complicate this method.

NV Integration: Together with the Jayich group at UCSB, we are exploring the possibility of a longer-range project, in which nitrogen-vacancy centers in diamond would serve as spin-resolving quantum sensors of single reversibly adsorbed atoms. A powerful new form of quantum gas microscopy is one of the exciting possible outcomes of this exploration; new tools for near-surface quantum sensing is another.

5 Collaborative Initiatives

Figure 8: The California Institute for Quantum Emulation unites efforts at UC Berkeley, UCLA, UC Irvine, UCSD, and UCSB.

Deep theory-experiment collaborations are essential for quantum emulation, and for continuing progress in the directions established by our AFOSR YIP-supported research. With this in mind, we along with our colleagues at other UC campuses have built the west coast's first collaborative quantum emulation institute. The PI of this AFOSR YIP award (Weld) is the lead PI of this new multicampus research institute, called the California Institute for Quantum Emulation (IQE, or CAIQuE). The IQE, funded initially by a President's Research Catalyst Award from The UC Office of the President, unifies theoretical and experimental approaches to quantum emulation research at five UC campuses. With our theoretical colleagues at UC Irvine, we have recently published the first collaborative paper from the IQE, describing a new type of quasiperiodic optical lattice created by a physical realization of the abstract cut-and-project construction underlying all quasicrystals [20]. Dynamical effects in such a lattice (including topological pumping and phason spectroscopy) can be understood as generalizations of the lattice modulation ideas first developed in our AFOSR YIP work; the exploration of quasiperiodic potentials in this context has developed into an entirely new and separate line of research for our group.

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Abstract

We have built an ultra-high vacuum experimental apparatus for trapping and cooling of strontium, demonstrated its operation, and used it to trap and cool all four stable isotopes of this alkaline earth metal. As part of the design and construction of this apparatus, we have developed a new type of atomic beam nozzle and a new type of permanent-magnet Zeeman slower. We have discovered and described a new cooling technique for degenerate bosonic quantum gases in optical lattices. We have developed the first theoretical treatment of a lattice-based quantum Kapitza pendulum, a novel Floquet system which we are investigating using modulated optical lattices. We have proposed and are developing new techniques of quantum gas microscopy and quantum sensing applicable to alkaline earth quantum gases. We have helped found a new collaborative institute for quantum emulation.

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Archival Publications (published) during reporting period:

Fibonacci Optical Lattices for Tunable Quantum Quasicrystals. K. Singh and D. M. Weld. arXiv:1504.06769 (2015).

Adiabatic cooling of bosons in lattices to magnetic ordering. J. Schachenmayer, D. M. Weld, H. Miyake, G. A. Siviloglou, A. J. Daley, and W. Ketterle. arXiv:1503.07466 (2015).

Effusive Atomic Oven Nozzle Design Using an Aligned Microcapillary Array. R. Senaratne, S. Rajagopal, Z. Geiger, K. Fujiwara, V. Lebedev, and D. M. Weld. Rev. Sci. Instrum. 86, 023105 (2015).

Self-assembled Zeeman slower based on spherical permanent magnets. V. Lebedev and D. M. Weld. J. Phys. B: At. Mol. Opt. Phys. 47, 155003 (2014). (Cover Article)

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

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Appendix Documents

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